WIDE BANDGAP EXTRINSIC PHOTOCONDUCTIVE SWITCHES*

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Abstract

Semi-insulating Silicon Carbide and Gallium Nitride are attractive materials for compact, high voltage, photoconducting semiconductor switches (PCSS) due to their large bandgap (3.0 – 3.4 eV), high critical electric field strength (3.0 – 3.5 MV/cm) and high electron saturation velocity ($2.0 – 2.5 \times 10^7$ cm/s). Carriers must be optically generated throughout the volume of the photoswitch to realize the benefits of the high bulk electric field strength of the 6H-SiC (3 MV/cm) and GaN (3.5 MV/Cm) materials. This is accomplished by optically exciting deep extrinsic levels in Vanadium compensated semi-insulating 6H-SiC and Iron compensated semi-insulating GaN. Photoconducting switches with opposing electrodes were fabricated on a-plane, 6H-SiC substrates and c-plane, GaN substrates. This work reports the initial fabrication and test of extrinsic GaN switches excited at a wavelength of 532 nm, and a review of the first phase [1] of switch tests of a-plane, 6H-SiC PCSS.

I. Introduction

Previous SiC PCSS work [2-4] used high resistivity, low impurity SiC polytypes and focused on lateral geometry surface switches that used above band-gap wavelengths of light to trigger the switches. The performance and switch life of lateral geometry PCSS are limited by surface flashover, surface carrier mobility and high current density. PCSS with opposing electrical contacts deposited on vanadium compensated, semi-insulating, 2H-GaN and 6H-SiC substrates can be triggered using below band-gap light to excite carriers from extrinsic levels throughout the bulk of the material. This results in diffuse photocurrent and switch hold off voltages determined by the bulk breakdown field strength of 2H-GaN and 6H-SiC materials. The bulk switching capability and semi-insulating nature of 6H-SiC and 2H-GaN are enabled by the addition of the dopants Vanadium and Iron. Vanadium is an amphoteric impurity that can act as a deep acceptor, or a deep donor in 6H-SiC. Vanadium acts as a deep acceptor when the nitrogen donor impurity density sufficiently exceeds the boron acceptor impurity density, which is the case for the 6H-SiC material we have tested. The Fermi level is pinned close to the Vanadium acceptor level (0.7 eV below conduction band) resulting in a semi-insulating material. The Vanadium

acceptor levels capture electrons donated from the shallow (0.08 eV below conduction band) Nitrogen donor levels. These captured electrons can be excited into the conduction band by photons with energies exceeding 0.7 eV. Figure 1 [5] depicts the extrinsic levels in the 6H-SiC bandgap. The defect levels include Silicon vacancies and the UD-1 defect [5]. Semi-insulating GaN utilizes an Iron acceptor level (0.5 – 0.6 eV below the conduction band) to compensate shallow Oxygen donors. Electrons that are captured by the Iron acceptor levels can be excited into the conduction band by photons with energies greater than 0.6 eV.
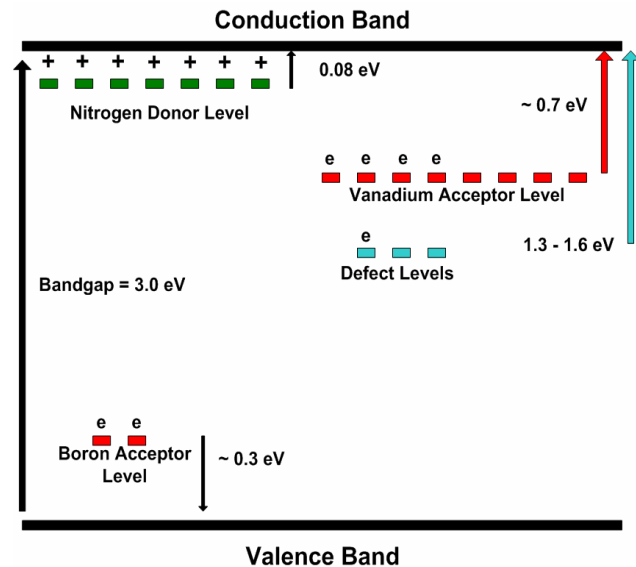

Figure 1. Vanadium acceptor and nitrogen donor levels in vanadium compensated 6H-SiC.

II. 6H-SiC Switch Test Results

A detailed presentation of the 6H-SiC switch test results has been previously reported [1]. Here we will present a brief review. Six PCSS devices were fabricated from samples of 400 μm thick, 1.2 cm per side, square substrates of "a" plane, vanadium compensated, semi-insulating 6H-SiC. The four facets of the substrate were cleaved/polished to enhance optical coupling into the bulk of the substrate. The contacts consist of a 0.8 cm diameter, circular metalization centered on opposing sides of the substrate. The metalization formed an ohmic contact and consisted of layers of nickel, titanium,

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14. ABSTRACT
Semi-insulating Silicon Carbide and Gallium Nitride are attractive materials for compact, high voltage, photoconducting semiconductor switches (PCSS) due to their large bandgap (3.0 3.4 eV), high critical electric field strength (3.0 3.5 MV/cm) and high electron saturation velocity (2.0 2.5x107 cm/s). Carriers must be optically generated throughout the volume of the photoswitch to realize the benefits of the high bulk electric field strength of the 6H-SiC (3 MV/cm) and GaN (3.5 MV/Cm) materials. This is accomplished by optically exciting deep extrinsic levels in Vanadium compensated semi-insulating 6H-SiC and Iron compensated semi-insulating GaN. Photoconducting switches with opposing electrodes were fabricated on aplane, 6H-SiC substrates and c-plane, GaN substrates. This work reports the initial fabrication and test of extrinsic GaN switches excited at a wavelength of 532 nm, and a review of the first phase [1] of switch tests of a-plane, 6H-SiC PCSS.

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platinum and gold. Indium coated copper electrodes were brazed to the substrate metalizations to facilitate electrical connection. The finished 6H-SiC PCSS assembly is shown in Figure 2. Photoconductivity tests were performed using 1064 nm and frequency doubled 532 nm wavelength light from a Q-switched Nd:YAG laser with an 8 ns at full wave half maximum (FWHM) output pulse. The optical pulse was focused and aligned to obtain as uniform as possible light pulse over a rectangular area measuring 1 cm wide by 400 μm high. The optical pulse was then centered on the PCSS facet. Photoconductivity tests were performed using optical pulse energies ranging from 1 to 14 mJ.

The photoconductivity of the PCSS was measured using the circuit shown in Figure 3. The 1.5 μF capacitor of the test circuit was pulse charged to bias voltages ranging from 250 V to 4.25 kV in 30 μs and the PCSS was optically triggered after a 30 μs flat top interval of the pulse bias voltage for the 6H-SiC device. The voltage across the PCSS was measured differentially using a pair of calibrated, fast (250 MHz bandwidth), high voltage (5 kV) probes. The load voltage was measured using a fast (35 ps rise time), low impedance (250 Ω) high voltage probe. A single switch was tested to failure at a charge voltage of 11 kV. Catastrophic failure occurred due to field enhancement at the edge of the electrode metalization. The PCSS current was obtained by dividing the load voltage by the load resistance. Dynamic switch resistance is another important switching parameter. The dynamic switch resistance is calculated by dividing the switch voltage by the load current. The minimum dynamic PCSS resistance is approximately constant for a fixed optical pulse energy, regardless of the bias voltage.

Figure 2. Vanadium compensated, semi-insulating, 6H-SiC PCSS assembly.

Switch minimum dynamic PCSS resistance as a function of optical pulse energy for 1064 and 532 nm wavelengths is shown in Figure 4. The switch minimum dynamic PCSS resistance decreases rapidly with optical pulse
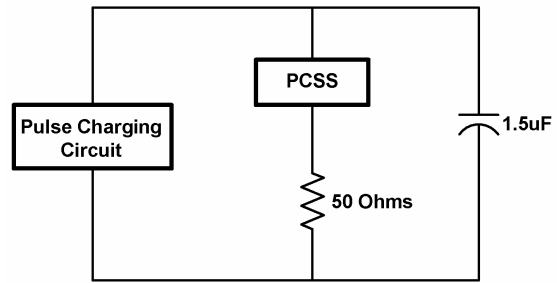

Figure 3. Simple schematic for PCSS photoconductivity test circuit.

energy for both optical wavelengths. The PCSS attains a lower minimum dynamic resistance at all optical energies for excitation with 532 nm light compared to excitation with 1064 nm light. This is a result of charge carriers being excited from additional extrinsic levels by the 532 nm wavelength.
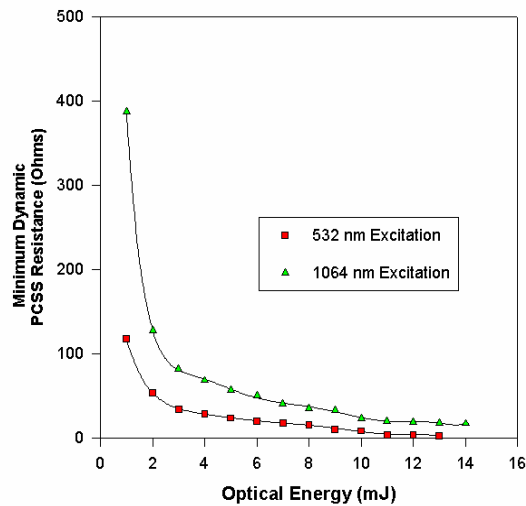

Figure 4. Minimum dynamic PCSS resistance as function of optical trigger energy for 532 and 1064 nm.

III. SiC and GaN Transmission Measurements

Optical transmission measurements were performed on a 7.2 mm by 3.7 mm, 400 μm thick, 6H-SiC substrate and a 9.0 mm by 9.0 mm, 408 μm thick, 2H-GaN substrate. The optical pulse passed through a 50/50 beam splitter and half the pulse was applied to a SiC, or GaN, substrate facet and the other half was applied to an optical energy meter. Optical pulses were applied to the 3.7 mm by 400 um facet of the 6H-SiC substrate with the optical E field perpendicular to the c direction of the SiC crystal. For the GaN substrate, the optical pulse was applied to the 9.0 mm by 408 μm facet with the optical E field vector parallel to the c direction of the GaN crystal. Both substrates were masked so that only light striking the facet

was transmitted to an optical energy meter positioned behind the substrate. The effective absorption was calculated from the transmission measurements using measured values of the index of refraction [6,7], assuming linear absorption and using equation (1).

$$T = \frac{(1-(\frac{n-1}{n+1})^2)^2 \exp(-\alpha l)}{1-(\exp(-\alpha l)(\frac{n-1}{n+1})^2)^2} \qquad (1)$$

Where T is the transmission, α is the effective linear absorption, l is the length traveled through the substrate and n is the index of refraction of either 6H-SiC, or GaN. Plots of the effective absorption as a function of optical energy are shown in Figure 5. It is apparent from some of the plots of Figure 5 that the absorption has a nonlinear component. We assume that the largest nonlinear component of the absorption is free carrier absorption. The materials with the largest nonlinear component indicate the better switch material at the given wavelength. On the other hand higher absorption translates to shallower optical penetration depths and smaller switch structures.
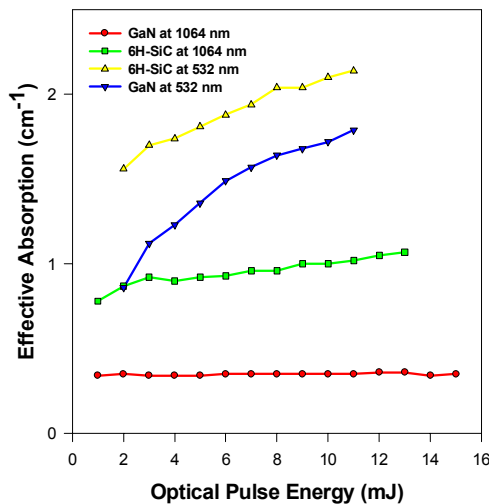

Figure 5. Effective optical absorption in GaN and SiC at 532 and 1064 nm

IV. GaN Switch Testing

A GaN switch assembly was fabricated using a 9 mm by 9 mm, 408 μm thick, semi-insulating substrate. The GaN substrate was epitaxially grown by Kyma Technologies. 6.5 mm diameter circular metallization layers were centered on both sides of the GaN substrate. The metallization consisted of layers of Titanium and Gold deposited by a liftoff technique. Copper electrodes were brazed to the substrate metallization using Indium solder.

The GaN switch assembly is similar to the SiC switch assembly of Figure 2. The GaN device was tested at bias voltages from 150 to 1000 volts using the same circuit as the 6H-SiC switch. Optical excitation at both 532 and 1064 nm were applied to the GaN switch. However, only a neglible amount of photocurrent was generated at 1064 nm. The results for excitation at 532 nm are shown below. Figure 6 shows the GaN switch voltage, current and optical excitation for a 1000 Volt charge voltage and 12 mJ of optical excitation at 532 nm. These results were obtained for an optical pulse that measured ~ 5.5ns (FWHM), significantly shorter than the optical pulses used to excite the 6H-SiC switch (8 ns FWHM). The general results of the GaN switch testing are summarized in Figures 7 and 8. Figure 7 shows the peak switch photocurrent as a function of optical excitation energy at a wavelength of for a variety of charge voltages. The saturation of the photocurrent begins at $3 - 4$ mJ of optical excitation for all charge voltages. The data shown in Figure 7 can be recast to show the peak photocurrent as a function of charge voltage for a range of optical excitation energies. The resulting plots are shown in Figure 8 and the linear nature of the GaN switch becomes apparent. The peak photocurrent is a linear function of bias voltage for excitation with a fixed optical energy. This indicates
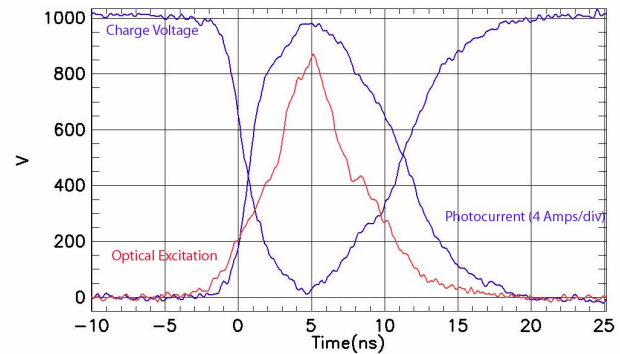

Figure 6. Switch voltage, photocurrent and optical excitation for GaN switch at 1000 Volts charge voltage and 12 mJ excitation at 532 nm.

that the total resistance of the test circuit is constant for a fixed applied optical energy. The circuit resistance calculated for a fixed applied optical energy of 0.5 and 12 mJ is 685.7 and 51.6 Ohms, respectively. The minimum GaN switch resistance is calculated by subtracting the 51 Ohm load resistance from the total circuit resistance, resulting in 634.7 and 0.6 Ohms, respectively for 0.5 and 12 mJ excitation.

V. Conclusions

Linear, extrinsic photoconductive switches have been fabricated from semi-insulating 6H-SiC and 2H-GaN substrates. Minimum switch resistances of 11 and 2 –3 Ohms have been demonstrated for 6H-SiC devices at 1064 and 532 nm excitation, respectively.

Minimum switch resistances of 1100 and 0.6 Ohms have been demonstrated for a 2H-GaN device at 1064 and 532 nm excitation, respectively. It appears that the shallow
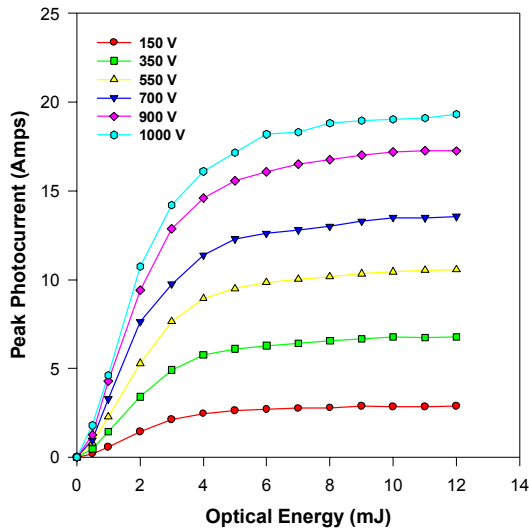

Figure 7. Peak photocurrent of GaN switch as function of optical excitation energy for range of charge voltages of 150 – 1000 Volts.
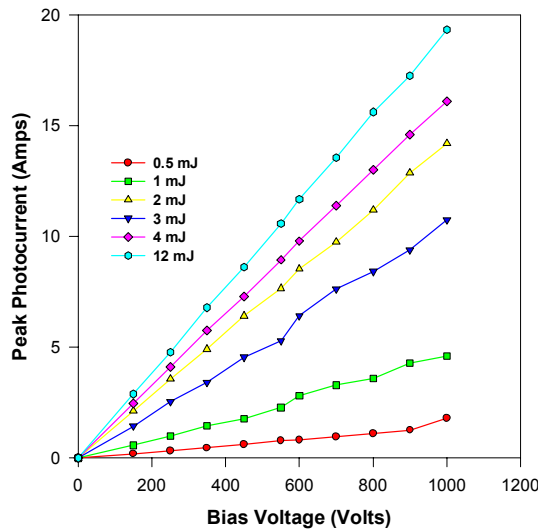

Figure 8. Peak photocurrent vs bias voltage for a range of 0.5 – 12 mJ in optical energies.

Nitrogen donor and deep Vanadium acceptor levels are key to the switching at 1064 nm in the 6H-SiC devices. The expected switching action using the shallow Oxygen donor and deep Iron acceptor levels in 2H-GaN was never manifested at 1064 nm excitation. Unknown deep levels exhibited strong switching action in GaN at 532 nm excitation. Future work will be to optimize the Nitrogen and Vanadium density in 6H-SiC for switching at 1064 nm and identifying deep levels in GaN that contribute to switching at 532 nm.

VI. Acknowledgement

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